Development and Deployment of an Extreme Turbulence (ET) Probe for Hurricane and High-Wind Research

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LONG-TERM GOALS

Turbulent exchanges of heat and momentum between the atmosphere and the underlying surface are a primary driving factor in the intensification and decline of tropical cyclones. Few in-situ observations of turbulence and surface fluxes have been made in the extreme environment associated with these tropical systems. Standard turbulence instruments are not designed to function in strong winds exceeding about 20 m s^{-1}, nor are they designed to function in heavy rain. An Extreme Turbulence (ET) probe is being developed to measure near-surface winds, turbulence, and fluxes in the high winds and precipitation rates encountered in tropical cyclones. This probe also has potential uses in other storms capable of producing high winds.

OBJECTIVES

The objectives of this project are:

1. To design, build, and test an ET probe suitable for deployment in the extreme conditions found within tropical cyclones or other storms associated with hurricane-force winds.
2. To deploy ET probes in the path of landfalling tropical cyclones to observe changes in winds, turbulence and surface fluxes as the storms move inland.
3. To collaborate with other scientists in deploying ET probes in high-wind conditions.

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These objectives fit into the overall goals of both the ONR Coupled Boundary Layers Air-Sea Transfer (CBLAST) initiative and the Hurricane at Landfall initiative sponsored by the U. S. Weather Research Program.

APPROACH

The project is developing a relatively low-cost, robust probe that can measure turbulent fluctuations in the high winds (> 30 m s^{-1}), heavy rain, and spray associated with strong tropical cyclones. The NOAA Air Resources Laboratory (ARL) has for many years used pressure-sphere anemometers (Brown et al. 1983; Crawford and Dobosy 1992) to measure turbulence quantities from fixed-wing aircraft. These devices, which have no moving parts, use pressure sensors connected to an array of holes on a spherical surface. The observed pressure distribution over the spherical surface is used to compute the magnitude and direction of the incident airflow. In aircraft applications, these anemometers are routinely operated at airspeeds of 50-60 m s^{-1} or higher, which correspond to at least a category 3 hurricane on the Saffir-Simpson scale.

On an aircraft probe, only a partial sphere with a few pressure ports pointing forward is needed. A ground-based probe needs to be omnidirectional, so a full sphere with ports evenly spaced around the equator is required. The Extreme Turbulence (ET) probe under development at ARL is designed around a 43 cm diameter spherical shell made from fiberglass-epoxy composite. Ten pressure ports are located on the sphere's equator at 36° intervals. Two other rows of ports are located 18º above and below the equator. In all, the probe has 30 ports connected to 20 differential pressure sensors and 6 absolute pressure sensors. Additionally, two temperature sensors are located in a small housing on top of the sphere.

Data from the ET probe are collected by a nearby computer. Raw pressure and temperature data are first digitized at 50 Hz. The processing software then uses the pressure data to search for the location of the wind stagnation point on the sphere. Data from the pressure sensors closest to the stagnation point are used to compute a 50 Hz time series of the ambient wind vector. As development proceeds, the processing software will include algorithms for filtering out the effects of rain and spray on the pressure data. Eventually, the system may include a satellite link or other wireless transmission technology to send data to a remote location out of harm's way.

Once prototypes of the ET probe are completed and tested, they will be deployed near the coast in the path of landfalling tropical cyclones. These deployments will be in collaboration with other scientific teams, as coordinated through the Hurricane Research Division of the NOAA Atlantic Oceanographic and Meteorological Laboratory.

WORK COMPLETED

Significant progress was made in the development and testing of the ET probe in Fiscal Year 2003. The software used for data acquisition was significantly revised, and now appears to be highly stable. It has operated continuously over multiple days without errors, which is a necessity for a successful deployment in the field.

Extensive field tests of the ET probe were conducted at the ARL Field Research Division (FRD) in Idaho Falls. Many of the tests were conducted with the probe mounted on a vehicle, allowing the probes to be tested at highway speeds up to 30-40 m s^{-1}. The road tests were highly encouraging, indicating that the probes are performing close to expectations, at least in dry conditions. FRD had also planned several static field tests of the ET probe operating next to a sonic anemometer. However, the spring of 2003 turned out to be significantly less windy than normal in Idaho, probably due to the unusually warm winter of 2002-2003. This provided few days when the ambient winds were high enough to operate the ET probe. One extensive set of static data was collected on 15 May, when the winds were marginally strong enough for the probe to operate.

Some effort also went into developing methods for providing statistical confidence intervals for the turbulence statistics generated by the ET probe. The main problem is that the turbulence time series have significant auto- and cross-correlations, making standard confidence intervals based on the sample size *n* inappropriate. An alternate approach based on Bayesian Monte Carlo Markov Chain (MCMC) simulations appears to have some potential in providing more realistic confidence intervals.

The plans for Fiscal Year 2003 originally included the development of a backflushing system to keep water and spray from fouling the pressure ports. Unfortunately, ONR funding for the project was not received until June 2003, which did not allow sufficient time for the development of the backflushing system before the onset of the 2003 hurricane season. The backflushing system development was therefore postponed so that ET probes could be readied for possible deployment.

An initial attempt was made in September 2002 to deploy ET probes along the Gulf Coast for Hurricane Isidore, but this was aborted due to mechanical problems with the vehicle used to transport the probes. This first effort was also hampered by the sudden death in August 2002 of Dr. Timothy Crawford, the original principal investigator on this project. A successful deployment was made in September 2003, when Hurricane Isabel made landfall along the North Carolina Coast as a category 2 hurricane. A three-person crew from ARL was able to place one of the probes in the path of the hurricane near the coast. The eyewall of Isabel passed over this probe.

RESULTS

ARL performed a series of road tests of the ET probes using a specially designed rig on a pickup truck. This rig allows the probe to be rotated about its vertical axis to ensure that it behaves consistently for different wind directions. A cup anemometer is mounted beside the ET probe for comparison purposes. Figure 1 shows the wind speeds from a road test with one of the ET probes. The truck made several passes along an east-west stretch of highway near Idaho Falls. Ambient winds were about 8 m s^{-1} on this day, so speeds below about 10 m s^{-1} in the figure represent periods when the truck was stopped or reversing direction. The sphere was rotated about 45° each time the truck reversed direction. Wind speeds from the probe closely track those from the cup anemometer. Our experience with several road tests of this type is that the ET probe provides accurate measurements of the wind vector in dry conditions. Such tests, however, do not provide information on the probe's ability to measure turbulence and flux statistics.

We also were able to perform one series of static ET probe tests on 15 May 2003 near a sonic anemometer operated by FRD. Mean winds were about 8-15 m s^{-1}, which are only marginally strong enough for the ET probe to operate. Nonetheless, the tests still provided useful data.

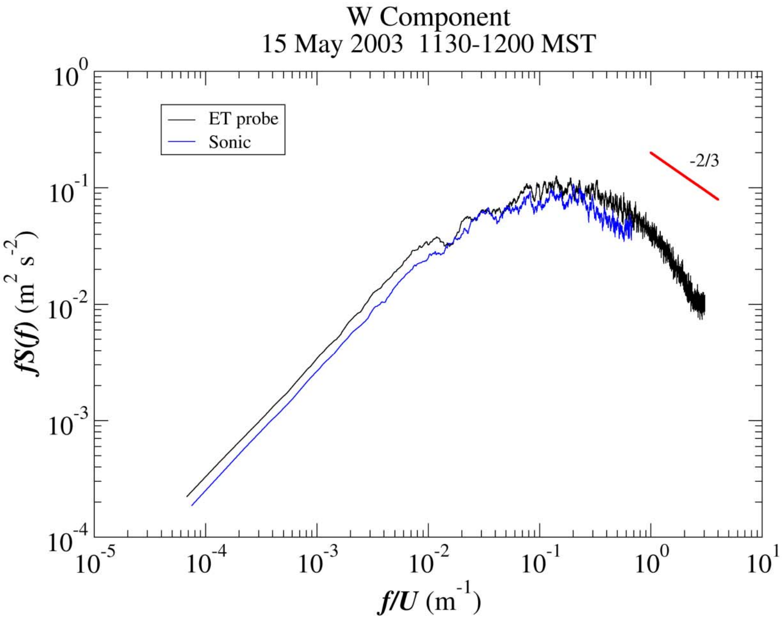

Fig. 1. Comparison of wind speeds from an ET probe and a cup anemometer during a road test in Idaho.

Figure 2 shows the vertical-velocity spectrum produced by both the ET probe and the sonic anemometer during a half-hour period on this day. The ET probe spectrum is somewhat higher, but the probe was also higher off the ground. In addition, the spectral rolloff at higher frequencies is greater than the -2/3 slope expected from inertial-subrange theory. This is probably related to the marginal wind speeds on this day, since the spectra from road tests at higher speeds seem to have the expected slopes.

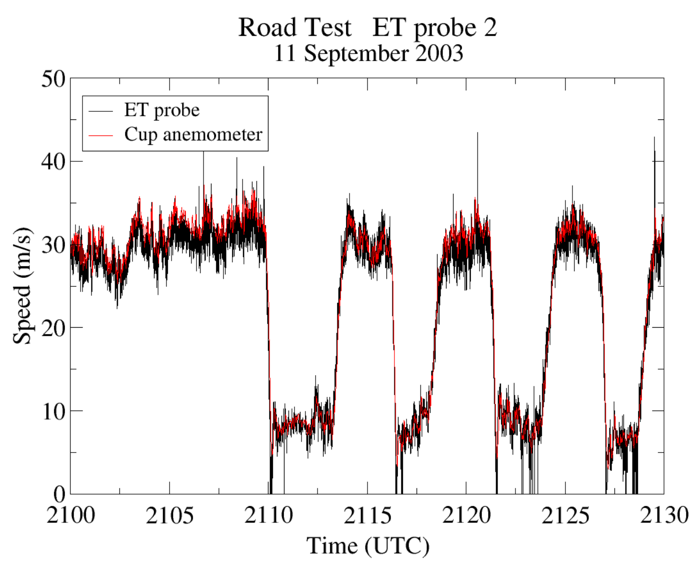

Fig. 2. Power spectra over a half-hour period for the vertical velocity from an ET probe and a sonic anemometer.

On 16 September 2003, a three-person crew from ARL traveled to North Carolina to deploy 2 ET probes in the path of Hurricane Isabel. One of the probes was installed at the airport in Beaufort, NC (Fig. 3), near the coast where the hurricane's eye was expected to make landfall. This probe was installed near a tower operated by Texas Tech University. Their tower included a sonic anemometer that will be valuable for comparisons with the ET probe. The second ET probe was significantly damaged during shipment; it could not be repaired in time for the landfall. Isabel made landfall on 18 September just north of the ET probe at Beaufort. The probe either went through the eye or was in the eyewall just south of the eye. It was retrieved on the following day with no significant damage, operating without error for over 36 hours. About 1.2 Gbytes of 50 Hz data were collected by the system. Analysis of the data was just beginning at the time this report was being written.

The Isabel deployment provided ARL with valuable experience in the logistics of hurricane deployments. It also indicated that the tower design developed for the ET probe is robust enough to stand up to a strong hurricane. Inspections of the system after the storm showed that water did enter the pressure-port tubing, and it likely affected the pressure measurements. A backflushing system for the pressure ports is expected to be a top development priority provided timely funding is available in 2004.

IMPACT/APPLICATION

The successful development of the ET probe will fulfill a need for turbulence and air-sea interaction data under high wind conditions. Standard turbulence instruments do not meet this need. The lack of air-surface exchange data in high winds is an important source of uncertainty in tropical cyclone modeling. ET probes have potential applications to other atmospheric phenomena involving high winds, including strong extratropical cyclones.

Fig. 3. Deployed ET probe on 17 September 2003 near Beaufort, NC. Hurricane Isabel made landfall the following day.

RELATED PROJECTS

The Air Resources Laboratory has two other CBLAST projects that involve anemometer technology similar to the ET probes. The CBLAST-Hurricane project (http://www.noaa.inel.gov/projects/cblast-hurricane/) has installed a pressure-sphere anemometer on one of the NOAA WP-3D hurricane-hunter aircraft. This system was successfully tested in Hurricanes Fabian and Isabel during the 2003 hurricane season. The CBLAST light-wind project (http://www.noaa.inel.gov/projects/cblast/) was using the NOAA Long-EZ aircraft with a pressure sphere to study maritime boundary-layer structure in weak winds, but this project was interrupted by the death of Dr. Timothy Crawford and the loss of the Long-EZ. However, analysis of data already collected is continuing.

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